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(54) Title: OPTICAL BRANCHING COMPONENT WITH LOW POLARISATION SENSITIVITY

(57) Abstract: An optical branching component particularly suitable for use as a tap device is described. The component has two optical waveguides in proximity with one another in at least two regions so as to form at least two adjacent directional couplers, and between the two directional couplers there is an effective optical path length difference between the two waveguides. The coupling strength of each of the two adjacent directional couplers monotonically decreases with increasing wavelength in the operational wavelength region of the component. This means couplers with relatively large coupling strength and relatively low polarisation dependent loss can be used in the component, giving low polarisation dependent variation in the tap ratio, particularly for small tap ratios.

OPTICAL BRANCHING COMPONENT WITH LOW POLARISATION SENSITIVITY

The present invention relates to optical branching devices, in particular optical branching devices provided in planar lightguide circuits (PLCs). More specifically, though not exclusively, the invention concerns an optical branching device having low polarisation dependent loss (PDL) for use as a tap device.

Optical branching components, also known as optical couplers, are well known and used in PLC technology. Different types of optical couplers exist, including directional couplers (such as shown in Fig.6) and Y-branch couplers. Directional couplers tend to have lower power loss than Y-branch couplers, but have higher wavelength dependency i.e. variation in the coupling strength with different input signal wavelengths.

US 5,044,715 describes an improved optical branching component, based on a Mach-Zender interferometer arrangement and which is designed to have low wavelength dependency. Fig.1 illustrates this component which comprises two waveguides which are brought into proximity with each other in two regions so as to form two directional couplers, there being an effective optical path length difference between the two waveguides where they extend between the two directional couplers. This effective optical path length difference is arranged to be less than the shortest operating wavelength of the branching component, and the directional couplers are each designed so that the coupling strength, C (where $C = \sin^2\varphi$, as described hereinbelow), of each directional coupler monotonically increases with increasing wavelength in the operational wavelength region of the component, as illustrated in the graph in Fig.2. Such a design is proposed to have low wavelength dependency and is sometimes referred to as a Wavelength Insensitive Coupler or WINC.

A desired application of a branching device like that described in US 5,044,715 is as an optical tap, to tap off a desired portion of the power in an optical signal input to the branching device. One disadvantage of using such a component as a tap is that the coupling strength of the individual directional couplers needs to be quite small for small tap ratios (where the tap ratio = $P_{tap} / (P_{tap}+P_{express})$, where P_{tap} is the output power in the tap path, and P_{exp} the output power in the express path). A big disadvantage of small coupling strengths is that a parameter which we refer to as the Relative Birefringence Error (RBE) becomes large, in particular where the PLC chip is fabricated in silica-on-silicon technology (which is a common technology platform for PLCs). A large RBE gives a large polarization dependence in the split ratio (where the "split ratio, P_{split}" of an individual coupler is defined as $P_{split} = P_1/(P_1 + P_2)$ where P_1 and P_2 are the power in the two output arms of the coupler respectively). When two couplers are combined in a Mach-Zender configuration this manifests itself as a high polarisation dependent deviation (>±0.2%) in the tap ratio. This polarization dependence in the tap ratio we shall refer to as the Polarization Dependent Loss or PDL of the tap channel, but it will be understood that strictly speaking the total power in the component is conserved, it is simply that the power in the tap channel is polarisation dependent.

This can cause significant problems for systems designers who wish to design such tap components into their systems. Component designers are continually trying to improve the performance specifications of PLC components, especially PDL in such components.

It is an aim of the present invention to avoid or minimise one or more of the foregoing disadvantages.

According to the invention there is provided an optical branching component comprising two optical waveguides which

are in proximity with one another in at least two regions so as to form at least two adjacent directional couplers, wherein between said two directional couplers there is an effective optical path length difference between the two waveguides, and wherein the coupling strength of each of said two directional couplers monotonically decreases with increasing wavelength in the operational wavelength region of the component.

An advantage of the inventive component, especially where the branching component is to be used as a tap, is that couplers with larger coupling strength can be used in the inventive component than in the WINC component of US 5,044,715, for a given tap ratio. These larger coupling strength couplers can be fabricated in silica-on-silicon technology to have a lower RBE than the prior art WINC, as will be later described, which in turn enables lower PDL to be achieved.

The coupling strength of each DC is preferably chosen so that a desired minimum PDL is achieved for each DC. The effective optical path length difference between the DCs may then also be optimised by the component designer, if desired, so as to minimise any wavelength sensitivity of the device in a given operational wavelength window of the device. For example, the effective optical path length difference, at a given operating wavelength (e.g. the lowest operating wavelength, or the central operating wavelength), may be chosen so that the wavelength sensitivity of the DCs is substantially offset by the wavelength sensitivity of the optical path length difference, over the operating wavelength window of the device.

Further inventive features of the invention are set out in the claims dependent from claim 1.

Preferred embodiments of the invention will now be described by way of example only and with reference to the accompanying drawings in which:

Fig.1 is a schematic plan view of a prior art WINC component, on a PLC;

Fig.2 is a graph illustrating the variation in the coupling strength of each directional coupler in the prior art WINC component of Fig.1, with variation in wavelength;

Fig.3 is a schematic plan view of an optical branching component according to the present invention;

Fig.4 is a perspective view of a portion of a waveguide in the component of Fig.3;

Fig.5 is a graph illustrating the variation in the coupling strength of each directional coupler in the inventive component of Fig.3;

Fig.6 is a plan schematic view of a directional coupler device;

Fig.7 shows three graphs plotting the RBE as a function of Gap, G, between the two waveguides of the straight section of each directional coupler in a Power Tap device of the Mach-Zender interferometer type shown in Figs 1 and 3, for three different waveguide core widths, based on modal and stress calculations;

Fig.8 is a graph plotting the PDL as a function of the RBE in a Power Tap device of the Mach-Zender interferometer type;

Fig.9 is a graph illustrating the variation in PDL with wavelength, for one embodiment of a PINC component according to the invention;

Fig.10 is a graph illustrating the variation in PDL with wavelength, for a prior art type WINC component like that of Figs.1 and 2;

Fig.11 is a graph illustrating the variation in the tap ratio with input signal wavelength, for the same PINC component as the Fig.9 graph; and

Fig.12 is a schematic plan view of a switching element according to another embodiment of the invention.

Fig.3 illustrates an optical branching component (or "optical coupler") according to the invention. In physical appearance, the component looks similar to the prior art WINC device of Fig.1, namely comprising two waveguides 10,12 which are brought into proximity with each other in two regions 13,14 so as to form two directional couplers (DCs). In the embodiment of Fig.3 the two waveguides have the same geometrical structure (i.e. dimensions of the core) and are made of identical materials. Like in the WINC device of Fig.1, there is an effective optical path length difference, $n\Delta L$, between the two waveguides where they extend between the two directional couplers, where ΔL is the physical length difference between the two waveguides and n is the (effective) refractive index of each waveguide. However, in contrast to the WINC device of Fig.1, in the device according to the present invention the DCs are designed so that the (power) coupling strength of each of the two DCs decreases monotonically with increasing wavelength, in the operating wavelength region of the device, as illustrated in Fig.5 and as will be later explained in detail.

The optical waveguides are silica-based waveguides formed on a silicon substrate using silica-on-silicon technology. Fig. 4 shows a portion (along the length) of such a waveguide comprising a core 15 etched from a core layer of silica-based material deposited on a silicon substrate 16 using Flame Hydrolysis Deposition. An undercladding layer 17 is commonly provided on the silicon substrate, prior to deposition of the core layer, and may be in the from of an

oxide layer or a layer of silica-based material. An upper cladding layer 18 covers and embeds the waveguide core and is formed using Flame Hydrolysis Deposition. In the preferred embodiment the core 15 is square in cross-section, having a core width, w (in the x and y-directions in Fig.4)

It can be shown that a quantity which we refer to as Relative Birefringence Error (RBE) heavily influences the performance of an optical coupler based on a Mach-Zender interferometer arrangement incorporating two directional couplers, like the devices illustrated in Figs. 1 and 3. The RBE can be used as a convenient indicator of the Polarisation Dependent Loss (PDL) of a component and we define the RBE as follows.

Definition of RBE

The performance of a directional coupler (DC) is determined by the overall phase thickness of the coupler. In the case of a symmetrical coupler comprising a continuously varying waveguide structure (in terms of the gap between the two waveguides, and core width of the waveguides), for example the DC shown in Fig.6, this phase thickness can be defined as half the phase shift between the fundamental and the first order modes in the coupler. This can also be expressed mathematically as:

$$\varphi = \int_{-L/2}^{L/2} \left|\kappa(G(z))\right| \cdot dz \quad \text{with} \quad |\kappa| = k_0 \frac{n_0(k_0) - n_1(k_0)}{2}.$$

where

κ is the coupling coefficient at location z in the coupler (as defined in "Optical Integrated Circuits" edited by Nishihara et al., page 42, and on page 60-61, edited by Donelley & Sons company);

$k_0 = 2\pi/\lambda$ is the wave-number in vacuum;

L is the length over which coupling contributes to the overall phase-thickness of the coupler ;

n_0 is the refractive index of the fundamental mode (of the optical signal beam field);

n_1 is the refractive index of the first order mode (of the optical signal beam field); and

G(z) is a function defining the width of the gap between the waveguides, as a function of z.

So if the polarization dependence of $n_0 - n_1$ is known as a function of the gap and the core width, then the polarization dependence of the phase thickness can be determined from the following:

$$\Delta|\kappa| = |\kappa|_{TM} - |\kappa|_{TE} = \frac{k_0}{2}\cdot\left(n_0^{TM} - n_0^{TE} - \left(n_1^{TM} - n_1^{TE}\right)\right)$$

$$= \frac{k_0}{2}\cdot\left(n_0^{TM,geo} + \Delta n_0^{TM,\sigma} - n_0^{TE,geo} + \Delta n_0^{TE,\sigma} - \left(n_1^{TM,geo} + \Delta n_1^{TM,\sigma} - n_1^{TE,geo} + \Delta n_1^{TE,\sigma}\right)\right)$$

$$= \frac{k_0}{2}\cdot\left(B_0^{geo} + B_0^{\sigma} - \left(B_1^{geo} + B_1^{\sigma}\right)\right)$$

where

$\Delta|\kappa|$ is the difference between the magnitude of the coupling coefficient for the TM polarisation ($|\kappa|_{TM}$) and the magnitude of the coupling coefficient for the TE polarisation ($|\kappa|_{TE}$); and

$B_i^{geo} = n_i^{TM,0} - n_i^{TE,0}$, which is the birefringence of the *i*th mode due to the geometrical structure (i.e. the dimensions) of the waveguides, and

$B_i^{\sigma} = \Delta n_i^{TM,\sigma} - \Delta n_i^{TE,\sigma}$, which is the birefringence of the *i*th mode due to stresses in the waveguides.

Assuming the polarization dependent effect to be small compared to the difference in propagation constant [i.e. k_0] of the fundamental and first order mode, a convenient relative quantity can de defined as:

$$RBE = \frac{\frac{k_0}{2} \cdot \left(B_0^{geo} + B_0^{\sigma} - \left(B_1^{geo} + B_1^{\sigma}\right)\right)}{\frac{k_0}{2} \cdot \left(n_0^{TE}(k_0) - n_1^{TE}(k_0)\right)} = \frac{\left(B_0^{geo} + B_0^{\sigma} - \left(B_1^{geo} + B_1^{\sigma}\right)\right)}{\left(n_0^{TE} - n_1^{TE}\right)} \approx \frac{\left(B_0^{geo} + B_0^{\sigma} - \left(B_1^{geo} + B_1^{\sigma}\right)\right)}{\left(n_0^{TM} - n_1^{TM}\right)}$$

Using this definition we obtain an integrated measure of the polarization dependence of the phase-thickness of the coupler:

$$\frac{\Delta\varphi}{\varphi} = \frac{\int_{-\infty}^{\infty} \frac{\left|\Delta\kappa(G(z))\right|}{\left|\kappa(G(z))\right|} \cdot \left|\kappa(G(z))\right| \cdot dz}{\int_{-\infty}^{\infty} \left|\kappa(G(z))\right| \cdot dz} = \frac{\int_{-\infty}^{\infty} RBE(G(z)) \cdot \left|\kappa(G(z))\right| \cdot dz}{\int_{-\infty}^{\infty} \left|\kappa(G(z))\right| \cdot dz}$$

where

$\Delta\varphi$ is the difference in phase thickness of the directional coupler, for the two different polarisation modes TM, TE

In fact $\Delta\varphi$ will also vary depending on whether the waveguides in the directional coupler are straight or are bent. As shown in Fig.6, typically the waveguides in a DC bend away from one either on either side of a middle portion 20 of the DC in which the two waveguides are straight and parallel. The waveguides will remain optically coupled in the bent region as they diverge away from one another until they diverge beyond a certain distance apart, d, at which they will no longer be optically coupled. In the bent sections of the coupler, the gap, G(z), is given by the following equation:

$G(z) = g_0 - 2R\left(\sqrt{1-(z/R)^2} - 1\right)$, where R = bend radius

Other Important Definitions include:

<u>Coupling length L_c</u>

$$L_c = \frac{\pi}{2} \cdot \frac{1}{\kappa(g_0, w_0)}$$

<u>Phase thickness due to the bend sections</u>

$$\varphi_{Bend} = 2 \cdot \int_0^R \kappa(G(z), w_0) \cdot dz$$

<u>Coupling length, L_B, of bend section</u>

$$L_B = \frac{\varphi_{bend}}{\pi/2} \cdot L_c$$

Fig.7 is a graph illustrating the variation in the RBE with the Gap, G, between the two waveguides, for a DC of a Power Tap device of the Mach-Zender interferometer type, in the straight section, L_s, of the coupler. Three graphs are shown for three different waveguide core widths, w = 4,5,6 μm, respectively. These graphs are all based on mode and stress computer simulations. From this it can clearly be seen that the larger the gap, the larger the RBE becomes, and therefore the higher the PDL. This is the case for all three core widths, w. The RBE is also higher, the greater the core width. Our goal is to achieve as low a value of RBE as possible in each DC. We further propose that in fact it is possible to use the different RBE values for the straight and bend sections of each DC to compensate one another, where the RBE in the straight section (RBE_s) and the total RBE from the bend sections (RBE_b) are of opposite sign. For example, we ma achieve a total RBE_T of zero for the DC where:

$$RBE_T = RBE_s + RBE_b = 0.$$

Fig.8 Shows a graph illustrating the linear relationship between PDL and RBE in a Power Tap of the Mach-Zender interferometer type, where it has been assumed for simplicity that the two DCs have identical RBE. The slope of the graph

will depend on the tap ratio and the choice of other device parameters. This graph is again based on mode and stress computer simulations. It can clearly be seen that the PDL increases linearly with increasing RBE.

In the WINC coupler described in US5,044,715 it is the case that in order to achieve a low tap ratio, say only a few percent or less, it is necessary to use directional couplers (DCs) with very small coupling strength. This is due to the requirement (for the WINC) that the coupling strength of the DCs must increase monotonically with increasing wavelength. The big disadvantage of DCs having small coupling strengths is that the RBE of such couplers becomes large. Particularly where the waveguides are fabricated in low index contrast technology, such as silica-on-silicon waveguides, the PDL of such WINCs will be large, typically 0.5dB or higher depending on the gap size. This is largely because to achieve the necessary "monotonically increasing" condition (to give the proposed wavelength insensitivity) the gap, G, between the waveguides in each DC has to be relatively large, typically greater than 3μm), and so does the width of the waveguide cores, typically a width above the maximum width for a monomode waveguide. As shown above, greater gap sizes, G, and/or greater core width, w, gives larger RBE.

In contrast, in the optical branching device of the present invention, illustrated in Fig.3, each DC has a coupling strength which decreases monotonically with increasing wavelength, in the operating wavelength region of the device. The advantage of this is that even where a small tap ratio is desired (say a few percent or less), the coupling strength of the DCs will be larger than in the WINC device. This means that we can design our DCs to have a smaller gap,G, between the waveguides and/or a smaller waveguide core width, w.

Decreasing the gap size and/or the core width increases the coupling strength of the couplers, but as a higher coupling strength is tolerable in our couplers (to achieve a given low tap ratio) this is acceptable. As above-explained, lower gap width G and/or lower waveguide core width, w, will give lower RBE, and hence lower PDL.

The way in which we design the DCs to have a coupling strength which decreases monotonically with wavelength will now be described. The term "coupling strength" with respect to a directional coupler will herein be understood to mean the power coupling strength, C, of the DC, where C is defined as:

$C = \sin^2\varphi$, where φ is the phase thickness of the DC, as already defined above.

In fact, the branching devices of Figs.1 and 3 are defined by three parameters:

The phase delay, 2θ, between the (two waveguides between the) two DCs;

The phase thickness, φ_1, of the first coupler;

The phase thickness, φ_2, of the second coupler.

The phase delay is related to the effective optical path length difference, $n\Delta L$, between the two DCs, by the following equation:

$$2\theta = 2\pi \cdot n\Delta L / \lambda$$

By choosing an appropriate value of θ it is possible to try to compensate the wavelength dependence of each DC by the wavelength dependence of the phased delay 2θ. This can be best explained by looking at the situation where two identical DCs of phase-thickness φ are used. The power coupling strength C_T of the entire Mach-Zender interferometer type branching component is given by:

$C_T = \sin^2(2\varphi) \cdot (1 + \cos 2\theta)/2$, where two identical DCs are used in the device.

With the required conditions on the WINC device of Fig.1, that the coupling strength of each DC increases monotonically with increasing wavelength, this sets the possible ranges of values for φ (e.g. $0 < \varphi < 90°$, or $180° < \varphi < 270°$). The value of θ can then be optimised so that the wavelength dependence of the $\sin^2(2\varphi)$ term is cancelled by the wavelength dependence of the $(1 + \cos 2\theta)/2$ term, so that the total coupling strength, C_T, of the WINC device is wavelength insensitive. For example, where $0 < \varphi < 45°$ the $\sin^2(2\varphi)$ term is increasing with increasing wavelength, so one needs to have $90° < \theta < 180°$ so that the $(1 + \cos 2\theta)/2$ term decreases with wavelength. US 5, 044,715 proposes that θ is set close to, but slightly under, 180° at the shortest operating wavelength of the device.

The two DCs need not be identical, they may each have a different phase thickness φ_1 , φ_2 in which case the total coupling strength, C_T, of the WINC is given by:

$$C_T = \sin^2(\varphi_1 + \varphi_2) \cdot (1 + \cos 2\theta)/2 + \sin^2(\varphi_1 - \varphi_2) \cdot (1 - \cos 2\theta)/2$$

In one embodiment of a branching device according to the present invention, we set the phase thickness of each DC so that:

$$90° \le \varphi_1 \le 180°$$

$$90° \le \varphi_2 \le 180°$$

In this case, the coupling strength, $C = \sin^2\varphi$, of each DC decreases monotonically with increasing wavelength in the operating wavelength region of the component, as illustrated in Fig.5. With these values of φ_1 and φ_2 , we have found that the RBE becomes small, namely less than 1%, possibly close to zero, for both the bend and straight sections of the

DCs, especially if the gap, G, between the DC waveguides is reduced to about 1μm, and the waveguide width, w, of the D waveguide cores is reduced to about 4μm. The small RBE means that the PDL will be low. In order to minimise any wavelength sensitivity, the value of θ is then also chosen so that again the wavelength sensitivity of the DCs is substantially compensated for by the wavelength sensitivity of the optical path length difference, by using the appropriate above equation defining the total coupling strength C_T of the overall branching device (depending on whether both DCs have identical phase thickness, or not). For example, where both DCs have the same phase thickness, and this phase thickness φ is between 90° and 135°, we would make $90° < \theta < 180°$, whereby again the increase with wavelength of the $\sin^2(2\varphi)$ term is substantially compensated for by the decrease with wavelength of the $(1 + \cos 2\theta)/2$ term. However, where the phase thickness φ is between 135° and 180° we would want to make $0° < \theta < 90°$, whereby the decrease with wavelength of the $\sin^2(2\varphi)$ term is substantially compensated for by the increase with wavelength of the $(1 + \cos 2\theta)/2$ term.

In a preferred embodiment of the present invention we have used the following values:

$\theta = 93.9°$

$\varphi_1 = 113.8°$

$\varphi_2 = 102.5°$

This has been found to give 0.14% RBE in the straight waveguide section of each DC, and -0.51% RBE in the bent sections.

Fig. 9 is a graph of PDL vs. wavelength, in the wavelength region between about 1520nm and 1570nm, for a PINC device according to the invention, designed as a 4% power tap with a gap between the waveguides of 1μm in the straight section 20

of each [redacted] and a RBE of 0.5% in each DC of the PINC. The lower line shows the PDL for the express signal path through the PINC, and the upper line is for the Tap path. These graphs were obtained from empirical (i.e. experimental) data. It can be clearly seen that the PDL values are very low, the highest PDL values being in the Tap path but always less than 0.15dB. Fig.10 is a similar graph, again obtained from empirical data, this time plotted for the express and tap paths in a prior art WINC device also designed as a 4% tap, with a gap of 3μm between the waveguides in the straight section of each DC of the WINC, and an RBE of 4% for each DC. In this case it can be seen that the PDL values in the Tap path are much higher than in the PINC device, never being less than 0.25dB and sometimes being greater than 0.45dB, giving a variation of about 0.2dB between the minimum and maximum PDL values.

Fig.11 illustrates the wavelength dependency of a PINC device according to one embodiment of the invention. It shows the variation in the Tap ratio of the PINC as a function of wavelength. This graph is again for a (approx.) 4% tap, gap of 1μm, and RBE of 0.5%, same as for graph of Fig.9. The tap ratio over the wavelength range 1520nm to 1640 nm is 3.57% ± 0.05% which is relatively low variation. Thus it can be readily seen from Figs.9 and 11 that the PINC component has very low polarisation dependent loss (PDL) in addition to having a tap ratio which is relatively wavelength insensitive in at least the 1520nm to 1640nm region, which is the desired operating wavelength region of our component.

Various modifications and variations to the above-described embodiments are possible without departing from the scope of the claimed invention. For example, variations in the waveguide dimensions and materials are possible, though may not give as good performance results in terms of the

wavelength-dependent loss (WDL) and PDL. Moreover, the waveguides need not be made using only FHD and etching technology - other process technologies could be used, for example Chemical Vapour Deposition (CVD).

Furthermore, the two waveguides 24,26 need not be identical in the invention. The power transfer in any coupler is governed by the coupling coefficient as well as by the phase-mismatch. In the above-described embodiment of the current invention we have assumed two identical waveguides thus resulting in zero phase-mismatch, thereby simplifying the design optimization, but the same principles could also be repeated for slightly or totally asymmetric couplers.

In other possible embodiments, one or more further waveguides may be incorporated into the device and arranged so that each directional coupler comprises three waveguides located in proximity to one another, in known fashion.

Alternatively, or additionally, one or more heater elements may be provided on the device, for varying the path length (in response to electrical signal(s) being applied to the heater(s)) of one or more of the waveguides so as to actively control the signal output(s) from the branching component, in known fashion. For example, the use of such heaters can enable the branching component to be used to perform switching operations. Fig. 12 shows one embodiment of a switching device incorporating two PINCs 40,42 according to the invention, separated by two delay paths 44,46 formed by the two waveguides of the device respectively, and with a heater a,b provided on each delay path.

CLAIMS

1. An optical branching component comprising two optical waveguides which are in proximity with one another in at least two regions so as to form at least two adjacent directional couplers, wherein between said two directional couplers there is an effective optical path length difference between the two waveguides, and wherein the coupling strength of each of said two directional couplers monotonically decreases with increasing wavelength in the operational wavelength region of the component.

2. An optical branching component according to claim 1, wherein each of said two directional couplers has the same coupling strength.

3. An optical branching component according to claim 1, wherein each of said two directional couplers has a different coupling strength.

4. An optical branching component according to any preceding claim, wherein the smallest gap between the two waveguides in each of said two directional couplers is less than 3μm.

5. An optical branching component according to claim 4, wherein the smallest gap between the two waveguides in each of said two directional couplers is approximately 1μm.

6. An optical branching component according to claim 5, wherein the width of the core of each waveguide is

approximately 4μm in a straight section of each of said two directional couplers.

7. An optical branching component according to any preceding claim, wherein the phase thickness of each of said two directional couplers is between 90° and 180 °.

8. An optical branching component according to any preceding claim, wherein said effective optical path length difference is less than the shortest operating wavelength of the component.

9. An optical branching component according to claim 2, wherein the phase thickness of each of said two directional couplers is between 90° and 135° and the phase delay, 2θ, between the two waveguides, between said two directional couplers, is defined by $90° < \theta < 180°$.

10. An optical branching component according to claim 2, wherein the phase thickness of each of said two directional couplers is between 135° and 180 ° and the phase delay, 2θ, between the two waveguides, between said two directional couplers, is defined by $0° < \theta < 90°$.

11. An optical branching component according to any preceding claim, wherein the magnitude of the RBE of each of said two directional couplers is less than 1%.

12. An optical branching component according to any preceding claim, wherein the magnitude of the RBE of

each of said two directional couplers is no greater than 0.5%.

13. An optical branching component according to any preceding claim, wherein the component is a tap device having a tap ratio of no greater than 4%.

14. An optical branching component according to any preceding claim, wherein the component is a tap device in which the variation in the tap ratio with wavelength is less than 0.1% over the operating wavelength region of the component.

15. An optical branching component according to claim 1, further including at least one further waveguide.

16. An optical branching component according to claim 1, further including heater means disposed on at least one said waveguide.

17. An optical branching component according to any of claims 1 to 16, wherein the waveguides are fabricated in silica-on-silicon technology.

18. An optical switching device comprising two optical branching components according to any of claims 1 to 15, further including at least one heater means.

19. An optical switching device according to claim 18, wherein the waveguides are fabricated in silica-on-silicon technology.

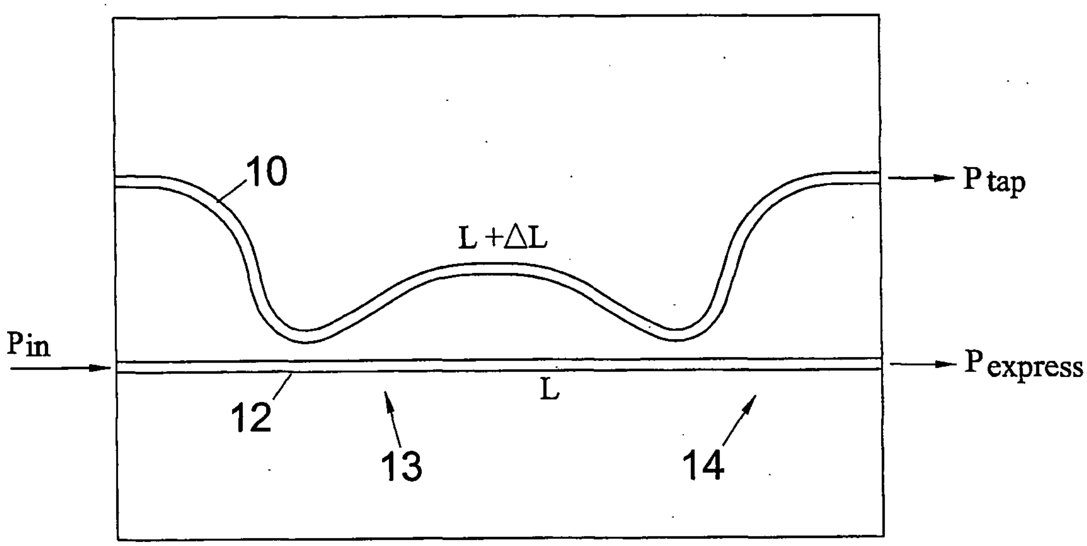
10
P tap
L +ΔL
Pin
P express
12
L
13
14

Fig. 1

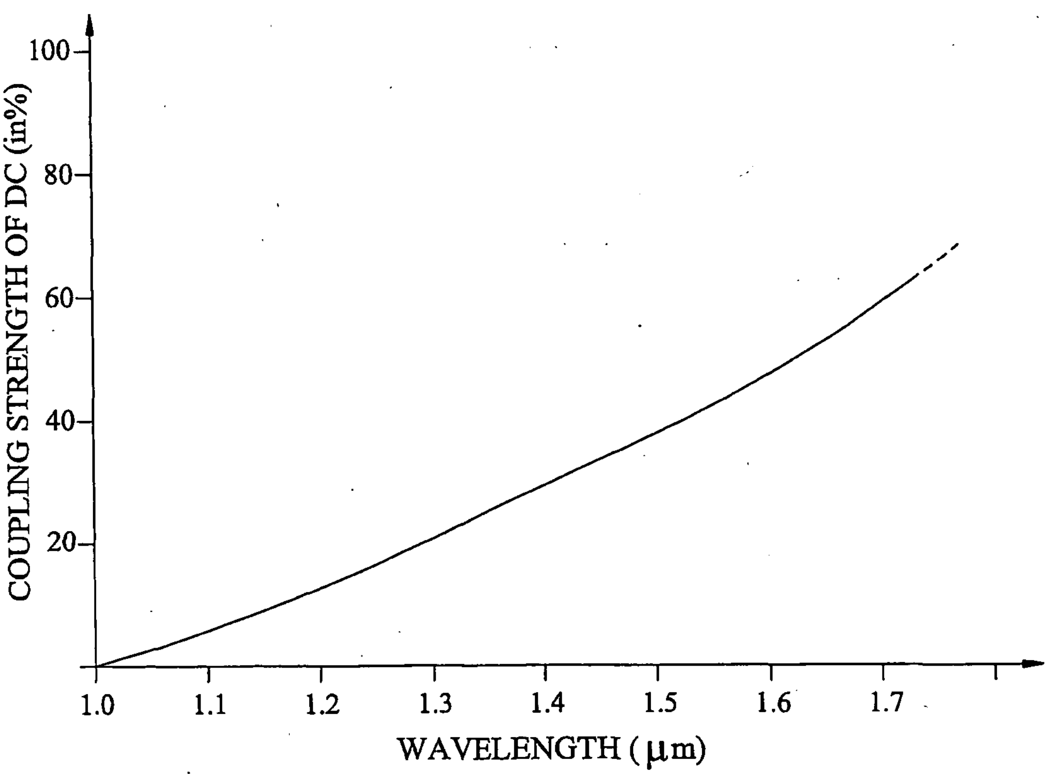
COUPLING STRENGTH OF DC (in%)
100
80
60
40
20
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
WAVELENGTH (μm)

Fig. 2

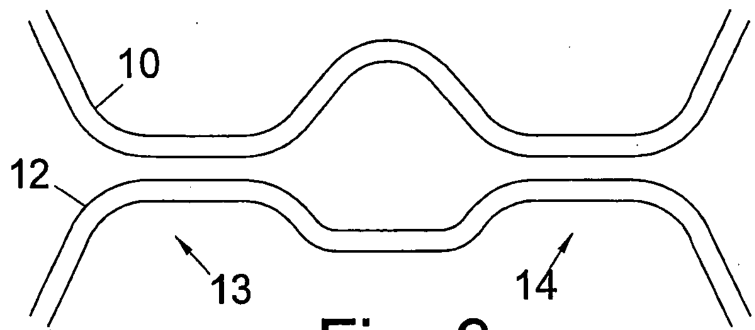

Fig. 3

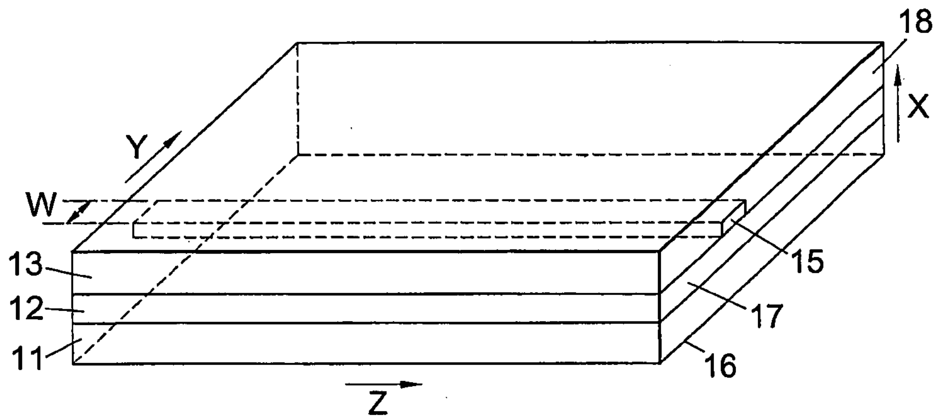

Fig. 4

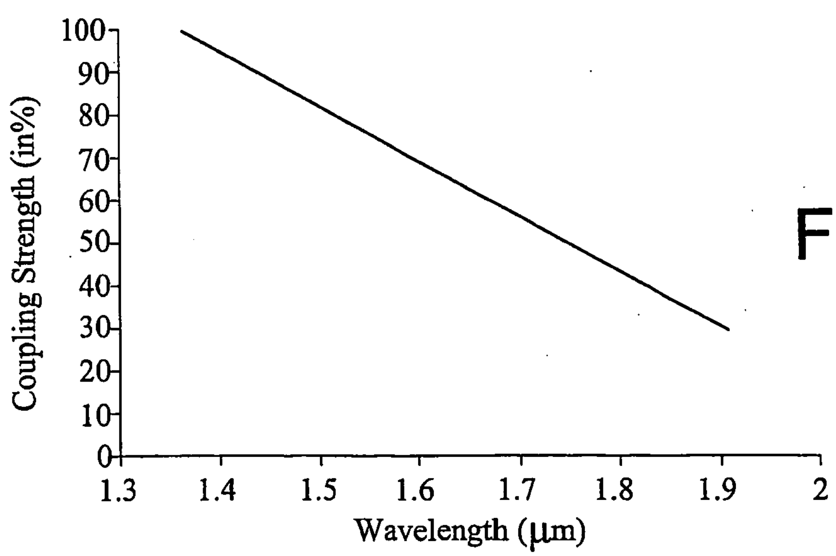

Fig. 5

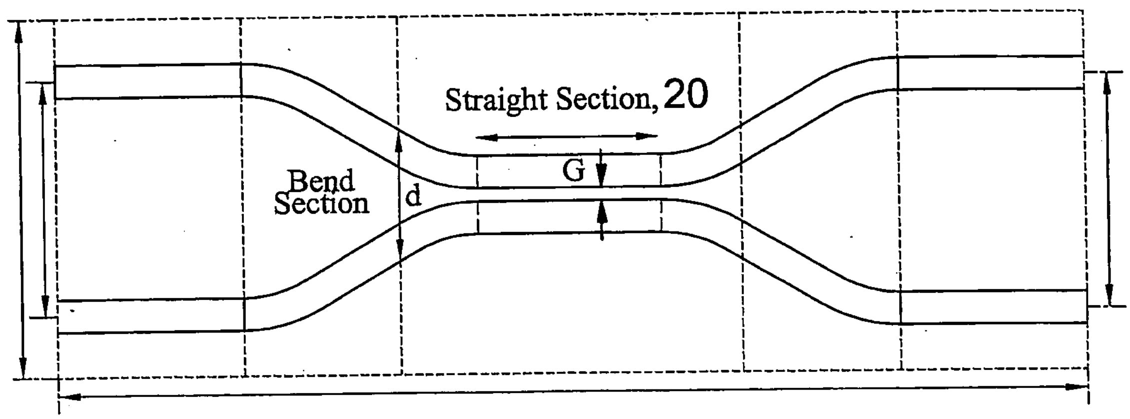

Fig. 6

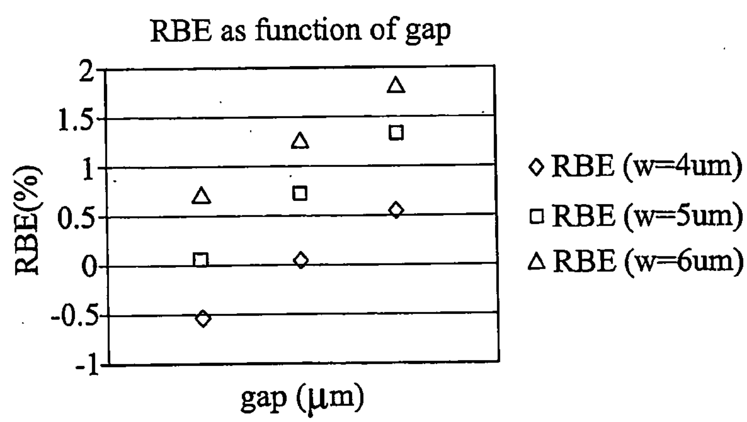

Fig. 7

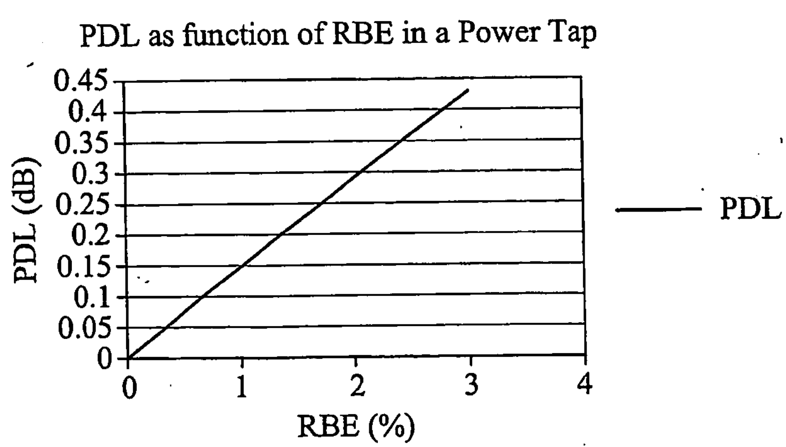

Fig. 8

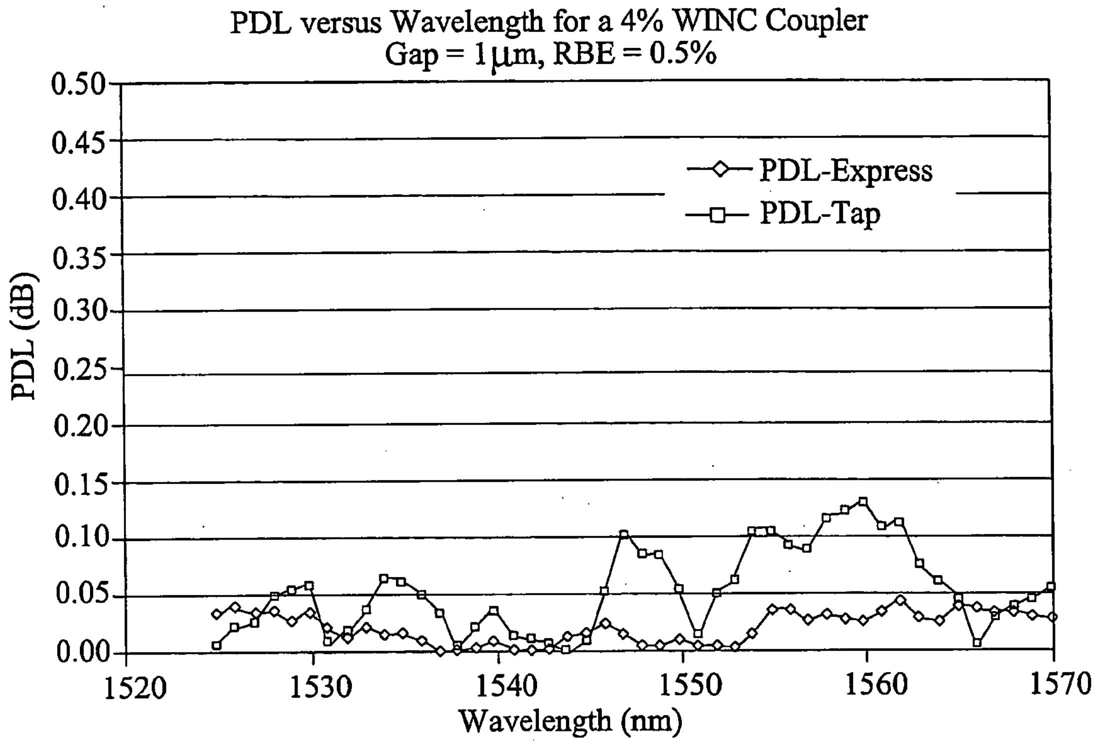
PDL versus Wavelength for a 4% WINC Coupler
Gap = 1 µm, RBE = 0.5%
PDL-Express
PDL-Tap
PDL (dB)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
1520
1530
1540
1550
1560
1570
Wavelength (nm)

Fig. 9

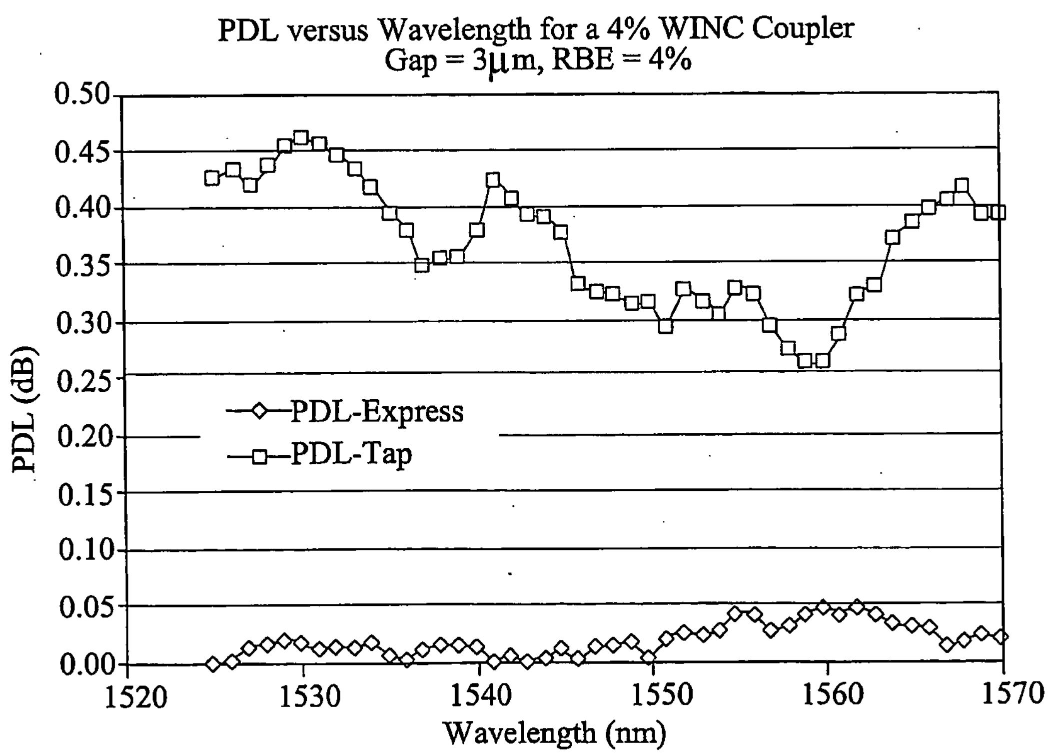
PDL versus Wavelength for a 4% WINC Coupler
Gap = 3µm, RBE = 4%
PDL-Express
PDL-Tap
PDL (dB)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
1520
1530
1540
1550
1560
1570
Wavelength (nm)

Fig. 10

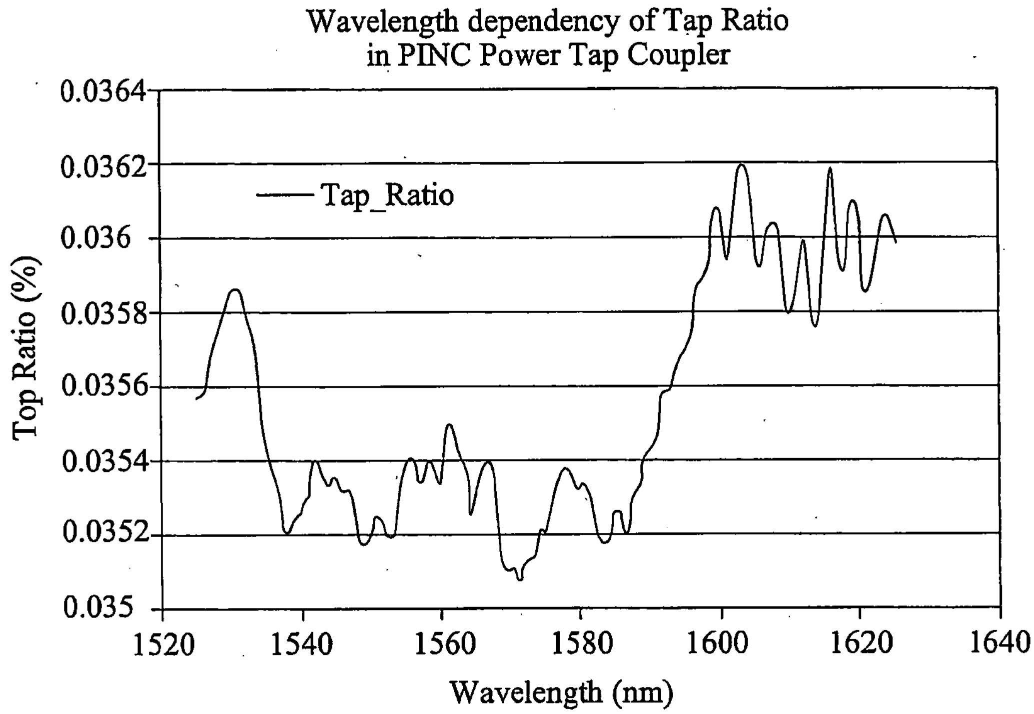
Wavelength dependency of Tap Ratio
in PINC Power Tap Coupler
Tap_Ratio
Top Ratio (%)
0.0364
0.0362
0.036
0.0358
0.0356
0.0354
0.0352
0.035
1520
1540
1560
1580
1600
1620
1640
Wavelength (nm)

Fig. 11

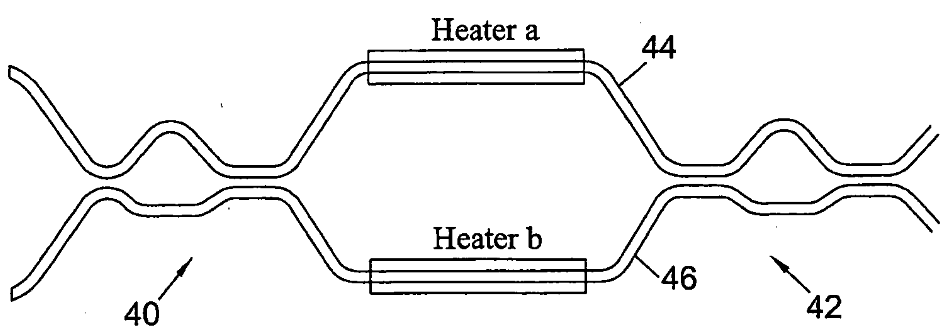
Heater a
44
Heater b
46
40
42

Fig. 12

INTERNATIONAL SEARCH REPORT

Internatio Application No
[redacted] 03/01071

A. CLASSIFICATION OF SU[redacted]**TTER**
IPC 7 G02B6/26 [redacted] G02B6/34

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 382 461 A (NIPPON TELEGRAPH & TELEPHONE) 16 August 1990 (1990-08-16) abstract figure 7 figure 9 page 9, line 21 - line 26	1-19
A	EP 0 610 973 A (FUJIKURA LTD) 17 August 1994 (1994-08-17) figures 6,7 page 6	1
A	PATENT ABSTRACTS OF JAPAN vol. 1996, no. 02, 29 February 1996 (1996-02-29) & JP 07 281041 A (HITACHI CABLE LTD), 27 October 1995 (1995-10-27) abstract	1

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
10 December 2003	17/12/2003

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Luck, W

INTERNATIONAL SEARCH REPORT

Inf ion on patent family members

Internatio pplication No
[redacted] 03/01071

Patent documen[redacted] cited in search repo[redacted]		Publication date	Patent family member(s)			Publication date
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			JP	7043484	B	15-05-1995
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			DE	69014602	T2	01-06-1995
			EP	0610973	A2	17-08-1994
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JP 07281041	A	27-10-1995	NONE			